

The lifetime of protoplanetary discs: Observations and Theory

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Abstract

The time-scale over which and modality by which young stellar objects (YSOs) disperse their circumstellar discs dramatically influences the eventual formation and evolution of planetary systems. By means of extensive radiative transfer (RT) modelling, we have developed a new set of diagnostic diagrams in the infrared colour-colour plane ($K - [24]$ vs. $K - [8]$), to aid with the classification of the evolutionary stage of YSOs from photometric observations. Our diagrams allow the differentiation of sources with un-evolved (primordial) discs from those evolving according to different clearing scenarios (e.g. homologous depletion vs. inside-out dispersal), as well as from sources that have already lost their disc. Classification of over 1500 sources in 15 nearby star-forming regions reveals that approximately 39 % of the sources lie in the primordial disc region, whereas between 31 % and 32 % disperse from the inside-out and up to 22 % of the sources have already lost their disc. Less than 2 % of the objects in our sample lie in the homogeneous draining regime. Time-scales for the transition phase are estimated to be typically a few 10^5 years independent of stellar mass. Therefore, regardless of spectral type, we conclude that currently available infrared photometric surveys point to fast (of order 10 % of the global disc lifetime) inside-out clearing as the preferred mode of disc dispersal.

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1 Introduction

The lifetime and modality for the dispersal of protoplanetary discs around newly formed low mass stars (approximately solar mass or lower) is a key parameter that influences the formation and evolution of eventual planetary systems. The classical picture that emerged from the last decade of photometric observations, mainly carried out with the Spitzer Space telescope is that of disc evolution being described by two different timescales. The first timescale could be defined as a ‘global timescale’, i.e. the total time it takes from a star to go from disc-bearing to disc-less, and a ‘dispersal timescale’, i.e. the time it takes for a disc to disappear once dispersal has set in. Global timescales, which can be inferred from the study of disc frequencies (e.g. Haisch et al. (2001)), are of order a few million years (e.g. Hernández et al. (2007); Mamajek (2009)). Dispersal time-scales, as determined from the study of infrared colours of young stars, appear to be much shorter, indicating that the

dispersal mechanism must be fast (e.g. Kenyon & Hartmann (1995); Luhman et al. (2010); Ercolano et al. (2011b)). Such observed two-timescale behaviour has favoured the development of disc dispersal models that involve a rapid disc clearing phase, contrary to the predictions of simple viscous draining, and in agreement with photoevaporation (Clarke et al., 2001; Alexander et al., 2006a,b; Ercolano, 2008; Ercolano et al., 2009; Gorti et al., 2009; Owen et al., 2010, 2011a,b, 2012) or possibly planet formation (Armitage & Hansen, 1999). The interpretation of infrared colours in relation to the evolutionary state of a disc is, however, far from being trivial. This is particularly true with regards to the classification of transition discs, the latter being intended as objects caught in the act of disc dispersal. The evolution of the dust component in a disc is mirrored by the evolution of colours in the infrared plane. By means of radiative transfer modelling, Ercolano, Clarke, & Hall (2011, henceforth ECH11) identified the regions in the K - [8] vs. K - [24] plane where primordial discs, discs with inner-holes (i.e. presumably being dispersed from the inside-out) and discs which lose mass homogeneously at all radii, are expected to be found. Their study, which was limited to M-stars, showed that in the case of the cluster IC348, most discs disperse from the inside-out and undergo the transition on a short time-scale, as predicted by standard photoionisation models. These conclusions are in contrast with the conclusions of Currie & Kenyon (2009), who claimed instead a large number of 'homogeneously depleting' discs, for the same cluster. Such discrepancies highlight the need for detailed modelling in the interpretation of IR colours of discs. The study of ECH11 was restricted to M-stars in only one cluster, which prevented the authors from being able to make a more general statement with regards to disc dispersal. Here we present results from a forthcoming paper (Koepferl et al., 2012), which significantly improves on the work of ECH11 by performing further RT calculation to evaluate evolutionary tracks in the IR colour plane for stars of different spectral types. We then apply our results to the photometric data of 15 nearby star-forming regions, that we collected from the literature, in order to address the question of what is the preferred mode of disc dispersal.

2 Disc evolution in the Infrared two colour plane

By means of radiative transfer modelling we identify 5 areas in the K - [8] vs. K - [24] plane corresponding to discs at different evolutionary stages or with different geometries, these are shown in Figure 1. Namely, primordial optically thick (flared and/or mixed) discs occupy area A, while disc-less objects cluster in area B and area C is for primordial ultra-settled (flat) discs. Discs that are in the act of dispersal belong to area D and E, where the former is for discs that are clearing from the inside-out, and the latter is for discs that are progressively going optically thin homogeneously at all discs radii (as would be expected from viscous evolution alone). Our classification scheme allows us to use currently available infrared photometric surveys from nearby star-forming regions in order to address the question of what is the preferential mode of disc dispersal. We therefore applied our colour-colour diagnostic diagrams to classify 1529 objects in 15 nearby star-forming regions. As an example, we overplot the data for Taurus (taken from Luhman et al. (2010)) to the diagnostic diagram in Figure 1. In summary, 39% of the objects out of the entire sample lie in the primordial disc region whereas between 31% and 32% disperse their discs from the inside-out and up to 22% of the sources have already lost their disc. So, almost a third of the available sources are currently clearing their discs from the inside-out. Less than 2% of the objects lie in the homogeneous draining region E. We interpret this result as strong evidence against homogeneous disc depletion as the main disc dispersal mode.

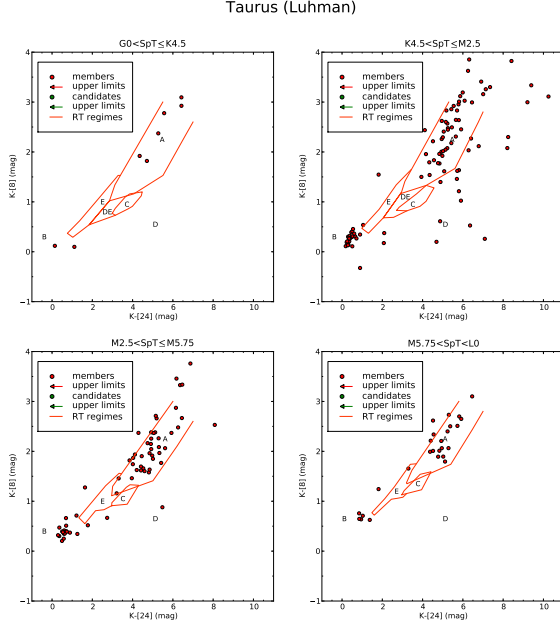


Figure 1: Disc evolution diagnostic diagram applied to the YSOs in the 1 Myr old cluster Taurus. 20 sample points lie outside the limits of this plot, but they are still included in the final statistics. (51 % primordial optically thick (A), 0 % primordial ultra-settled (C), 23 % disc-less (B), 14 % inside-out clearing (D), < 1 % homogeneous draining (E)).

3 Dispersal time-scales across spectral types

With the sample of YSOs in different star-forming regions becoming larger and larger, it is now possible to estimate the typical time-scales for the disc dispersal phase, even though cluster ages of course always introduce a large uncertainty in the estimates. The disc-evolution time-scale of a star-forming region can be roughly estimated by multiplying the age of the region by the ratio of the number of evolved object to the total number of objects in the region. Typical transition time-scales for the considered star-forming regions are of order 10^5 yrs. The average time-scale across all spectral types is $6.9 \cdot 10^5$ yrs and roughly the same as the average cluster time-scale of $6.6 \cdot 10^5$ yrs. This is partially because there is no significant difference for timescales amongst spectral types. We further illustrate that disc dispersal time-scales appear to be independent of spectral type. We plot in Figure 2, the time-scale ratio between K and M-stars and show that this ratio is consistent with unity. This suggests that there is no significant dependence of the time-scale on stellar mass, as has already been pointed out by Ercolano et al. (2011a), who performed a spatial analysis of the distribution of K and M-stars with discs in young star-forming regions and found no significant difference in the distributions.

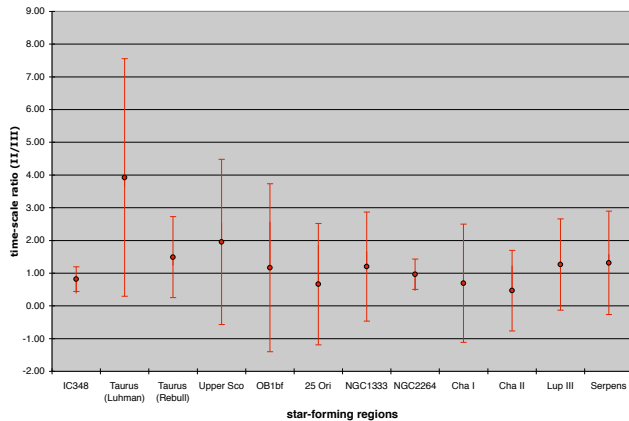


Figure 2: Time-scale ratio $\tau_{\text{II}}/\tau_{\text{III}}$ for K and M stars for the star-forming regions considered in this work with $N_{\text{tot}} > 10$. Three star-forming regions are not listed, because they lack evolving objects in one or both spectral type intervals.

4 Summary

We have calculated the SEDs of protoplanetary discs of different spectral types, geometries, settling and inclination. We then considered the evolution of the infrared colours ($K - [8]$ vs. $K - [24]$) of the model disks as they disperse according to different scenarios (homologous depletion, inside-out and outside-in clearing). Based on our models we propose a new diagnostic infrared colour-colour diagram to classify the evolutionary stage of YSOs. We have applied our infrared colour-colour diagnostic diagram to classify YSOs in 15 nearby star-forming regions and study the evolution of their disc populations. We estimate time-scales for transition phase of typically a few 10^5 years independent of stellar mass. We conclude that, regardless of spectral type, current observations point to fast inside-out clearing as the preferred mode of disc dispersal.

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